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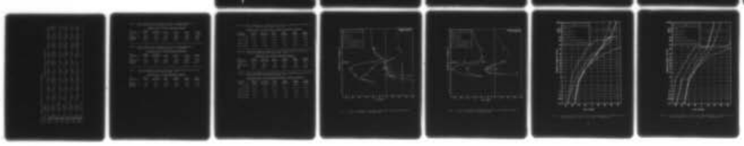

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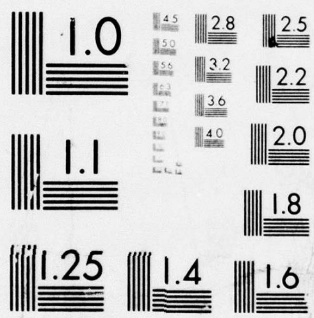

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UNITED STATES AIR FORCE
AIR WEATHER SERVICE (MAC)

USAF ENVIRONMENTAL TECHNICAL APPLICATIONS CENTER

SCOTT AIR FORCE BASE, ILLINOIS 62225

Report 8035 (Revised)

AN EVALUATION OF SEVERAL MODELS FOR DESCRIBING THE ATMOSPHERIC WATER-VAPOR PROFILE ABOVE THE $-40^{\circ}C$ TEMPERATURE LEVEL

by

Laurence D. Mendenhall, Capt, USAF

May 1977

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This technical report has been reviewed and is approved for publication.

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Conventional meteorological radiosonde humidity data are not reliable above the $-40^{\circ}C$ temperature level. An evaluation of several models used to describe the water-vapor profile above the $-40^{\circ}C$ temperature level, using frost-point data obtained from the Naval Research Laboratory (NRL), revealed that a simple model performed as well as more complex models to calculate the precipitable water. This model incorporates estimates of the frost-point temperature at the tropopause calculated with a regression equation,

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a hygropause fixed at 1 km above the tropopause and an interpolated value of the mixing ratio. The error in precipitable water and in the transmissivity in the 2.95 μm band served as the principal means for judging the performance of the models.

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Preface

Air Weather Service (AWS) requested that USAFETAC investigate the feasibility of using a simpler model of the water-vapor profile above the -40°C temperature level in the AWS point-analysis program. This report presents the results of that investigation.

In the event that this report is incorporated into another report by the requestor or any other agency, request that USAFETAC be given credit and furnished a copy of the new report when such dissemination is not prohibited.

USAFETAC prepared this report to document the results of a specific study. Further questions on this or related problems should be referred to USAFETAC for consultation and study.

The author gratefully acknowledges the contributions to the work reported herein made by Major Thomas Stanton and Capt Harry Henderson. Their work on the MOD2 and the regression equations, respectively, was done prior to their departure from USAFETAC in 1975.

AN EVALUATION OF SEVERAL MODELS FOR DESCRIBING THE ATMOSPHERIC WATER-VAPOR PROFILE ABOVE THE -40°C TEMPERATURE LEVEL

Introduction

Users of the Air Weather Service (AWS) point-analysis program require reliable water-vapor profiles from the surface to the lower stratosphere. However, conventional radiosonde data do not produce reliable humidity measurements in the region above the -40°C temperature level. In 1975, USAFETAC performed an analysis of Naval Research Laboratory (NRL) frost-point measurements and from this analysis constructed a regression model to describe the water-vapor profile above the -40°C temperature level. The results of this analysis and modeling effort, reported on in USAFETAC Report 7584 [4], were encouraging. Based on these results, particularly those of the transmissivity analysis, customers recommended [1] that AWS incorporate the new model into the operational point-analysis computer code. However, before doing this, AWS asked USAFETAC to investigate the simplification of the model. This report contains the results of that investigation and updates USAFETAC Report 8035 [5]. An error analysis compares the results from each of the models with the NRL frost-point soundings used as "ground truth."

Modification of the New Model

The new model reported on in Report 7584 [4] used a linear-regression technique to estimate the frost points at the tropopause (TFOOKM), at 1 km above and below the tropopause (TFPLS1 and TFMNS1), and at 2 km above and below the tropopause (TFPLS2 and TFMNS2). The model also used a regression estimate of the height of the hygropause (HMIXXX) and established frost-point values that yielded mixing ratios of 3 ppm at the hygropause (as defined in USAFETAC Report 7584 [4]) and 0.5 km above the hygropause. These estimated frost points, together with the observed frost points at the -40°C temperature level and at 0.5 km below the -40°C temperature level, were then used in an Aitken-Lagrange interpolation scheme to calculate the frost points at 0.5 km intermediate intervals. The predictors for the regression estimates of the frost points at the five levels at and about the tropopause included:

a. TF - (Variable No. 2) the frost points at that level estimated from the nine observed frost points at 0.5 km intervals down from the -40°C temperature level,

b. DELTAH - (Variable No. 3) the distance between the tropopause and the -40°C temperature level,

c. G1A - (Variable No. 4) the average lapse rate in the first kilometer above the tropopause (°C/km),

d. G3A - (Variable No. 5) the average lapse rate in the first 3 km above the tropopause (°C/km),

e. G1B - (Variable No. 6) the average lapse rate in the first kilometer below the tropopause (°C/km),

f. G3B - (Variable No. 7) the average lapse rate in the first 3 km below the tropopause (°C/km),

g. T - (Variable No. 8) the temperature at the particular level (°C),

h. P - (Variable No. 9) the pressure at the particular level (mb), and

i. ALOGP - (Variable No. 10) the natural logarithm of pressure.

The variable ALOGP accounted for most of the reduction of variance in the frost-point estimates (see Tables 9 through 13 in Report 7584 [4]). The lapse rates for the first kilometer above and below the tropopause and for the first 3 km below the tropopause and the temperature at the particular level collectively served to reduce the variance of the frost-point estimates another 5 to 20 percent. Consequently, it appeared that dropping the other predictors from the regression equations would probably not significantly affect the performance of the model. Furthermore, since the hygropause generally occurred about 1 km above the tropopause, it appeared that we

could assign a fixed value (1 km) to it and eliminate the need to estimate the hygropause height and the frost points at 1 and 2 km above the tropopause, TFP1KM and TFP2KM, respectively. Thus, the streamlined version (hereafter referred to as MOD1A) of the new model reported on in Report 7584 [4] (hereafter referred to as MOD1) requires regression estimates of only the frost point at the tropopause (TFOOKM), and at 1 and 2 km below the tropopause, TFM1KM and TFM2KM, respectively. Predictors for these predictands are as follows:

a. for TFOOKM: G1A, G1B, G3B, T, ALOGP.

b. for TFM1KM: G3B, T, ALOGP.

c. for TFM2KM: T.

The results of the regression analysis appear in Tables 3 through 5. An explanation of these tables along with the correlation matrices appears in Report 7584 [4]. The variable numbers referred to in Tables 3-5 in this report and in Tables 9-13 in Report 7584 [4] refer to the predictors, each assigned a variable number, as given in the list a. through i. on page 1. The regression equations used in MOD1 and MOD1A take the form

$$y = RI + A\times TF + B\times DELTAH + C\times G1A + D\times G3A + E\times G1B + F\times G3B + G\times T + H\times P + I\times ALOGP \tag{1}$$

where y is the predictand, RI is the intercept value, and A thru I are the coefficients for the predictors. The predictors are defined above. Table 6 gives the intercept values and the coefficients for the predictors for each predictand used in MOD1 and MOD1A.

A New Mixing-Ratio Model

The current effort included an evaluation of a simple mixing-ratio model. This model, coded by Maj Thomas E. Stanton in 1975, but not reported on in Report 7584 [4], used the regression estimates for the tropopause frost point and the 3 ppm value for the mixing ratio at the hygropause, the height of which is also estimated from regression as in the models described above. From these values, mixing ratios are interpolated logarithmically in pressure between the tropopause and the -40°C temperature level, and between the tropopause and the hygropause. A second version of this model uses a fixed value of the hygropause height of 1 km above the tropopause as in model MOD1A described above. These mixing-ratio models are hereafter referred to as MOD2 and MOD2A, respectively.

Comparison of Performance of the Models

This section describes the performance of six water-vapor models. Report 7584 [4] described the development of one of these, i.e., MOD1, while this report describes the simplification of that model, i.e., MOD1A, in addition to two other models, i.e., MOD2 and MOD2A. The following summarizes the salient characteristics of the six models:

a. Mixing ratio - the original moisture model used in the point analysis program. This model interpolates logarithmically in pressure between the 2 ppm mixing ratio at 150 mb and the observed value at the -40°C temperature level.

b. Frost-point depression - the model currently employed in the point-analysis program. This model interpolates logarithmically in pressure between the frost-point depression corresponding to a mixing ratio of 2 ppm at the 150 mb level and the frost-point depression observed at the -40°C temperature level.

c. MOD1 - the model described in Report 7584 [4]. This model uses regression estimates of the frost point at five levels, the tropopause and 1 and 2 km above and below the tropopause, and a regression estimate of the hygropause height. The regression estimates use nine predictors, one of which is a regression estimate at the frost point at that level, estimated from nine observed frost points at and below the -40°C temperature level. An Aitken-Lagrange interpolation scheme "fills" in the frost points at 0.5 km intervals.

d. MOD1A - similar to MOD1, except regression estimates of frost points are done at only three levels (tropopause, 1 and 2 km below tropopause) and only five predictors are used for the tropopause frost point, three for TFM1KM, and one for TFM2KM. No frost points are used as predictors.

e. MOD2 - a simple model, using the same regression estimates for the frost point at the tropopause and for the hygropause height as used in MOD1. Mixing ratios are interpolated logarithmically in pressure between a value of 3 ppm at the hygropause and the value estimated at the tropopause and between the tropopause value and the observed value at the -40°C temperature level.

f. MOD2A - same as MOD2 except it uses the regression estimate of the frost point as done in MOD1A. Hygropause fixed at 1 km above the tropopause.

Two methods were used to compare the performance of the six models. The first method used the cumulative precipitable water in a vertical column from 10 km above the tropopause downward to the -40°C temperature level. The second method used the transmissivity in the 2.95 μm band in a slant path, i.e., zenith angle of 80°, from 100 km to the -40°C temperature level. Two sets of data served as the references for these model comparisons. The first set consisted of the 101 NRL frost-point soundings, taken in 1964-1973, used to develop the regression coefficients, i.e., the dependent data set. The second set, serving as an independent data set, consisted of 14 NRL soundings taken during 1974-1976. Report 7584 [4] contains details of the instrumentation used to obtain the frost-point soundings as well as the dates/times of the observations. The dates/times of the independent data appear in Table 1 of this report, while Table 2 summarizes these data by tropopause pressure.

The results of the model comparisons for cumulative precipitable water in a vertical column from 10 km above the tropopause downward to the -40°C temperature level appears in Figures 1 thru 4 and in Tables 7 and 8. Results for dependent and independent NRL frost point data, i.e., "ground truth," appear separately. Figures 1 and 2 show the average error, $\bar{\varepsilon}$, in cumulative precipitable water as a function of altitude for the dependent and independent data, respectively, where

$$\bar{\varepsilon}(\text{percent}) = \sum_{i=1}^{n} \varepsilon_i \qquad (2)$$

and

$$\varepsilon_i(\text{percent}) = 100(W_m - W_o)/W_o \qquad (3)$$

Here ε_i is the percentage error in the cumulative precipitable water at a given height, W_m is the modeled value of the cumulative precipitable water, in the vertical column from 10 km above the tropopause to the given height, and W_o is the cumulative precipitable water in the same column calculated from the NRL observed data. Also shown on these figures is the standard deviation of the percentage error at selected levels and the total number of soundings used at each level. The latter decreases with decreasing height since a sounding is not included at a given level if its temperature at that level is warmer than -40°C.

[For example, in Figure 1 we see that the number of soundings used in comparisons decreased from the maximum available of 101 levels at heights higher than 3 km above the tropopause to only nine at 5 km below the tropopause. This simply reflects the fact that for all of the soundings the -40°C temperature level occurred at heights 3 km <u>above</u> the tropopause or less but that for nine soundings the -40°C temperature level was more than 5 km <u>below</u> the tropopause.]

The mean error, $\bar{\varepsilon}$, in the stratosphere results from the choice of the value used for the constant mixing ratio and could be reduced to near zero by choosing 2.7 ppm rather than 3 ppm as used in the four new models or the value of 2 ppm used in the two old models. Below the tropopause the four new models all show relatively small errors in the mean for the first few kilometers below the tropopause. However, for those cases where the -40°C temperature level is more than 3 km below the tropopause, the new models tend to overestimate the water vapor.

Figures 1 and 2 show how the mean error varies with the distance from the tropopause, while Tables 7 and 8 show some statistics of the error at the -40°C temperature level, the base of the modeled region. In these tables the column thickness varies since the height of the -40°C temperature level varies relative to the tropopause. The one-tailed Student-t test revealed no significant difference at the 0.05 level between the means of the four new models, but the difference in the means between any one of the new models and each of the two old models, i.e., the mixing-ratio and frost-point depression models, was significant at the 0.05 level. Figures 3 and 4 show the distributions of these errors in the cumulative precipitable water at the -40°C temperature level for the dependent and independent data, respectively.

The results of the model comparisons, using as the criterion the error in transmissivity in the 2.95 μm band along a slant path (zenith angle of 80°), appear in Tables 9 thru 12. Details of the method used to calculate the transmissivity appear in Report 7584A [3]. The use of transmissivities constitutes a more meaningful comparison for the customer than a comparison of precipitable water since transmissivity relates directly to system performance. The one-tailed Student-t test revealed no significant difference at the 0.05 level between the means of the four new models. However, a significant difference did exist at the 0.01 level for the independent data between the means for each of the new models and the frost-point depression model, the model currently in use in the point-analysis program. Tables 10 and 12 give the distributions of the absolute value of the errors for each of the models for the dependent and independent data, respectively.

Thus, the model comparisons just described reveal two significant facts. First, no significant difference exists, in a statistical sense, between the mean errors in either cumulative precipitable water or transmissivity in a vertical column or slant path, respectively, with bases at the -40°C temperature level. However, and secondly, the new models did demonstrate a statistically significant reduction in the mean errors for both cumulative precipitable water and transmissivity over the means for the two old models. Similar results can be seen for the number of cases with absolute errors of various magnitudes (Tables 10 and 12).

Conclusions and Recommendations

Any one of the four new models will result in substantial improvements in defining the water-vapor profile above the -40°C temperature level over that obtained with the currently used frost-point depression model. Using as a criterion the error in transmissivity from 100 km to the -40°C temperature level at a zenith angle of 80°, the simplest model, i.e., the new mixing-ratio model, MOD2A, performs equally as well as the more complex models, MOD1, MOD1A, and MOD2. However, this model may not perform as well as the more complex models in describing the entire vertical profile of water vapor above the -40°C temperature level, (see, for example, Figures 1 and 2). Therefore, for the purpose of describing the total precipitable water or, more specifically, the transmissivity in the 2.95 μm band in a slant path down to the -40°C temperature level, MOD2A could be incorporated into the point-analysis program instead of the more complex models, i.e., MOD1, MOD1A, and MOD2.

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[4] Mendenhall, L. D., Stanton, T. E., and Henderson, H. W.: "A Model for Describing the Atmospheric Water-Vapor Profile Above the -40°C Temperature Level," USAFETAC Report 7584, 20 August 1975.

[5] Mendenhall, L. D.: "An Evaluation of Several Models for Describing the Atmospheric Water-Vapor Profile Above the -40°C Temperature Level," USAFETAC Report 8035, August 1977.

Table 1. List of NRL Frost-Point Soundings Used as Independent Data (all at Washington DC).

No.	Date	Time	Tropopause Pressure (mb)
1	1/30/74	1500	220.00
2	4/26/74	1530	198.00
3	7/ 2/74	1530	175.00
4	9/13/74	1550	125.00
5	1/ 1/74	1645	156.00
6	2/20/75	1630	229.50
7	4/14/75	1630	198.00
8	5/14/75	1616	196.00
9	7/ 2/75	1730	158.00
10	9/30/75	1543	135.00
11	10/23/75	1540	188.00
12	11/ 5/75	2035	178.50
13	1/ 2/76	1648	206.00
14	4/ 6/76	1913	222.00

Table 2. Distribution of Tropopause Pressures for NRL Data Listed in Table 1.

Class Interval (mb)	Number of Soundings
$100<p<150$	2
$150\leq p<200$	8
$200\leq p<250$	4
$250\leq p<300$	0
$300\leq p$	0

Table 3. Regression Analyses for TFOOKM (Frost Point at the Tropopause)

VARIABLE ENTERED	7
SUM OF SQUARES REDUCED IN THIS STEP	63.608
PROPORTION REDUCED IN THIS STEP	0.015
CUMULATIVE SUM OF SQUARES REDUCED	3304.221
CUMULATIVE PROPORTION REDUCED	0.800 of 4131.246

FOR 5 VARIABLES ENTERED

MULTIPLE CORRELATION COEFFICIENT	0.894
(ADJUSTED FOR D.F.)	0.890
F-VALUE FOR ANALYSIS OF VARIANCE	79.906
STANDARD ERROR OF ESTIMATE	2.876
(ADJUSTED FOR D.F.)	2.932

VARIABLE NUMBER	REGRESSION COEFFICIENT	STD.ERROR OF REG. COEFF.	COMPUTED T-VALUE	PROPORTION REDUCED
10	6.384	2.968	2.151	66.1
6	-0.843	0.290	-2.910	9.1
4	0.450	0.131	3.441	1.6
8	0.418	0.109	3.828	1.7
7	-1.186	0.428	-2.773	1.5

INTERCEPT -88.054

Table 4. Regression Analyses for TFM1KM (Frost Point 1 km Below Tropopause)

VARIABLE ENTERED 8
SUM OF SQUARES REDUCED IN THIS STEP 216.739
PROPORTION REDUCED IN THIS STEP 0.038
CUMULATIVE SUM OF SQUARES REDUCED 4559.055
CUMULATIVE PROPORTION REDUCED . . . . 0.802 of 5683.563
FOR 3 VARIABLES ENTERED
MULTIPLE CORRELATION COEFFICIENT . . . 0.896
(ADJUSTED FOR D.F.) 0.893
F-VALUE FOR ANALYSIS OF VARIANCE 137.845
STANDARD ERROR OF ESTIMATE 2.757
(ADJUSTED FOR D.F.) 2.869

VARIABLE NUMBER	REGRESSION COEFFICIENT	STD.ERROR OF REG. COEFF.	COMPUTED T-VALUE	PROPORTION REDUCED
10	4.801	3.195	1.502	63.0
7	-2.531	0.275	-9.219	13.4
8	0.503	0.114	4.434	3.8

INTERCEPT -75.49

Table 5. Regression Analyses for TFM2KM (Frost Point 2 km Below Tropopause)

VARIABLE ENTERED 8
SUM OF SQUARES REDUCED IN THIS STEP 4724.098
PROPORTION REDUCED IN THIS STEP 0.669
CUMULATIVE SUM OF SQUARES REDUCED 4724.098
CUMULATIVE PROPORTION REDUCED . . . . 0.669 of 7062.250
FOR 1 VARIABLES ENTERED
MULTIPLE CORRELATION COEFFICIENT . . . 0.818
(ADJUSTED FOR D.F.) 0.818
F-VALUE FOR ANALYSIS OF VARIANCE 210.126
STANDARD ERROR OF ESTIMATE 4.742
(ADJUSTED FOR D.F.) 4.742

VARIABLE NUMBER	REGRESSION COEFFICIENT	STD.ERROR OF REG. COEFF.	COMPUTED T-VALUE	PROPORTION REDUCED
8	0.894	0.0617	14.496	66.9

INTERCEPT -11.617

Table 6. Regression Coefficients Used in MOD1 and MOD1A

Predictand		Intercept RI	A	B	C	D	E	F	G	H	I
			Coefficients for the Predictors								
TF00KM	MOD1	-109.72	0.1601	-0.4874	0.2243	0.9471	0.7899	-1.404	0.7173	-0.08132	18.49
	MOD1A	-88.05	0.0	0.0	0.4504	0.0	-0.8429	-1.186	0.4179	0.0	6.384
TFP1KM	MOD1A	-46.12	0.01685	-0.2512	-0.8299	0.1617	-1.045	-0.3684	0.3003	0.04939	-5.004
	MOD1A	Not used									
TFM1KM	MOD1	-21.57	0.3431	-0.2054	0.1558	-0.1304	0.1767	-2.479	0.5406	0.02209	-1.795
	MOD1A	-75.49	0.0	0.0	0.0	0.0	0.0	-2.531	0.5033	0.0	-4.801
TFP2KM	MOD1	-30.36	0.405	0.9935	0.1213	-0.4015	-0.8597	0.8792	-0.1617	0.08911	-6.954
	MOD1A	Not used									
TFM2KM	MOD1	-37.64	0.5045	1.760	0.09572	-0.1869	0.1400	-1.593	0.1827	0.01578	2.000
	MOD1A	-11.62	0.0	0.0	0.0	0.0	0.0	0.0	0.8942	0.0	0.0
HMIXXX	MOD1	-12.90	0.07564	0.08417	-0.01596	-0.1103	0.0	-0.02773	-0.04242	0.01025	-2.134
	MOD1A	Not used									

Table 7. Model Comparisons of Statistics of Error in Precipitable Water in Column from 10 km Above Tropopause to the T = -40°C Level

Dependent Data - 101 NRL Soundings 1964-1973

Error (percent)	Mixing Ratio	Frost Point Dep	MOD1	MOD1A	MOD2	MOD2A
Mean	-12.8	-37.0	-0.87	-12.9	-2.42	-3.08
Standard Dev	26.7	27.5	27.1	49.6	23.9	23.5
Minimum	-69.2	-75.5	-71.7	-53.6	-51.7	-50.6
Maximum	+68.3	+136.2	+126.9	+157.5	+61.1	+59.1

Table 8. Model Comparisons of Statistics of Error in Precipitable Water in Column from 10 km Above Tropopause to the T = -40°C Level

Independent Data - 14 NRL Soundings 1974-1976

Error (percent)	Mixing Ratio	Frost-Point Dep	MOD1	MOD1A	MOD2	MOD2A
Mean	-32.1	-47.3	- 3.9	- 6.1	-12.09	-11.7
Standard Dev	23.8	23.8	42.1	58.2	36.8	37.4
Minimum	-75.5	-82.9	-58.0	-39.3	-60.5	-58.5
Maximum	+21.3	21.1	+127.2	+172.4	+102.0	+106.1

Table 9. Model Comparisons of Statistice of Error in Transmissivity from 100 km to the T = -40°C Level for Zenith Angle = 80°.

Dependent Data - 101 NRL Soundings 1964-1973

Error (percent)	Mixing Ratio	Frost-Point Dep	New (MOD1)	New (MOD1A)	New (MOD2)	New (MOD2A)
Mean	2.4	7.2	0.9	- 0.5	0.9	1.0
Standard Dev	5.1	4.9	4.4	6.7	3.9	3.8
Minimum	-10.5	- 6.3	-12.1	-16.8	- 8.3	- 8.7
Maximum	13.5	18.4	19.9	13.7	10.6	10.7

Table 10. Model Comparisons of Absolute Value of Error in Transmissivity from 100 km to the T = -40°C Level for Zenith Angle = 80°.

Dependent Data - 101 NRL Soundings 1964-1973 (Percent Frequency)

Absolute of Error	Mixing Ratio	Frost-Point Dep	New (MOD1)	New (MOD1A)	New (MOD2)	New (MOD2A)
0 to ±5%	64.35	28.71	77.22	52.47	81.18	85.14
±5% to ±10%	27.72	41.58	19.80	34.65	17.82	13.86
±10% to ±15%	7.92	23.76	1.98	8.91	0.99	0.00
±15% to ±20%	0.00	5.94	0.99	3.96	0.00	0.00

Table 11. Model Comparisons of Statistics of Error in Transmissivity from 100 km to the T = -40°C Level for Zenith Angle = 80°.

Independent Data - 14 NRL Soundings 1974-1976

Error (percent)	Mixing Ratio	Frost-Point Dep	New (MOD1)	New (MOD1A)	New (MOD2)	New (MOD2A)
Mean	6.4	9.8	2.1	1.3	3.3	3.3
Standard Dev	5.7	6.1	5.5	6.3	5.2	5.1
Min	-2.2	-2.1	-10.5	-13.2	-8.5	-8.8
Max	20.9	24.5	14.8	8.9	15.4	14.8

Table 12. Model Comparisons of Absolute Value of Error in Transmissivity from 100 km to the T = -40°C Level for Zenith Angle = 80°.

Independent Data - 14 NRL Soundings 1974-1976 (Percent Frequency)

Absolute Error	Mixing Ratio	Frost-Point Dep	New (MOD1)	New (MOD1A)	New (MOD2)	New (MOD2A)
0 to ±5%	42.86	21.43	64.29	57.15	57.14	57.14
±5% to ±10%	35.71	35.71	21.43	35.71	35.71	35.71
±10% to ±15%	14.29	28.57	14.28	7.14	0.00	7.14
±15% to ±20%	0.00	7.14	0.00	0.00	7.14	0.00
±20% to ±25%	7.14	7.14	0.00	0.00	0.00	0.00

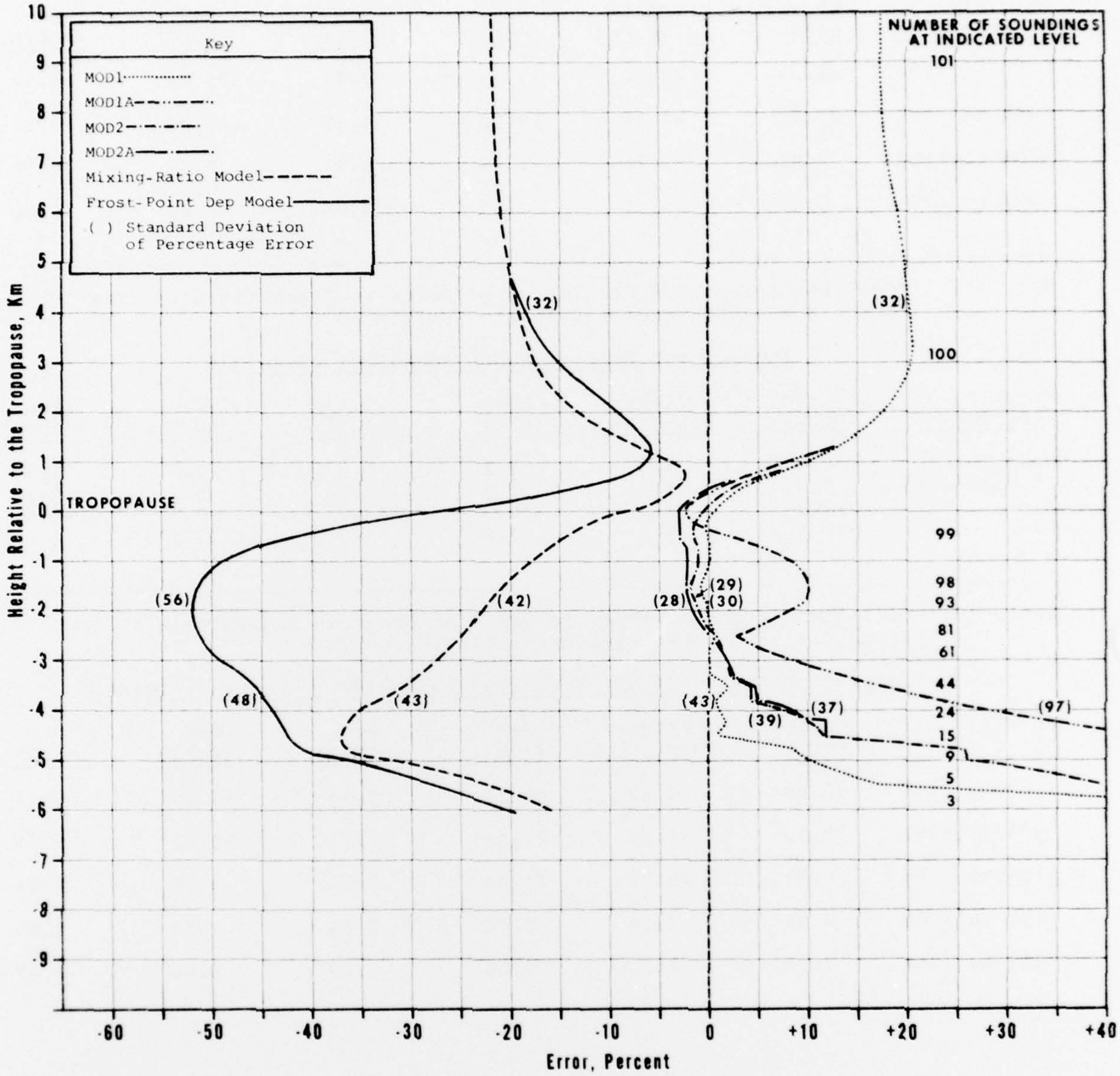

Figure 1. Error in Cumulative Precipitable Water from 10 km Above Tropopause to the T = -40°C Level - Dependent Data

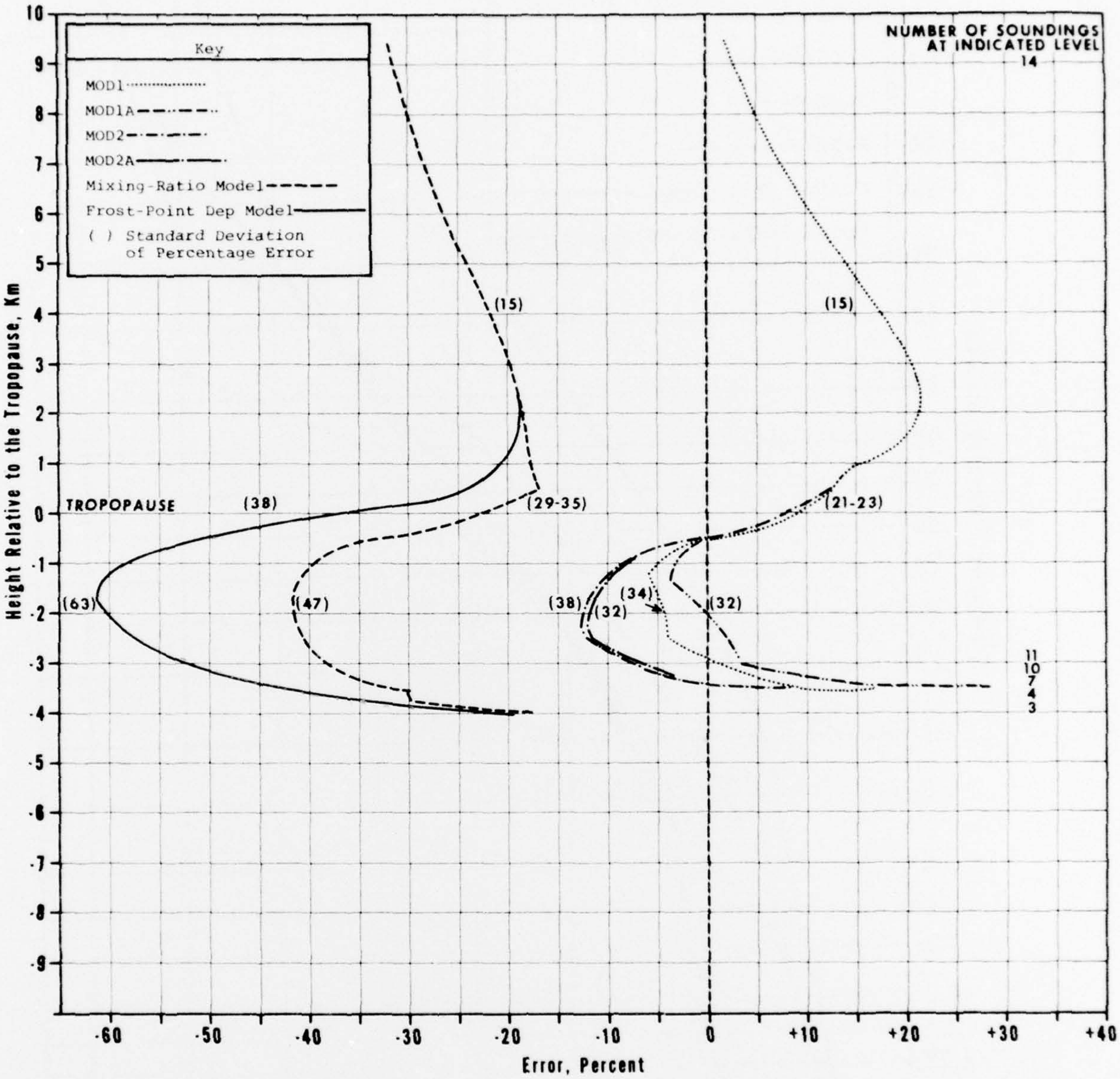

Figure 2. Error in Cumulative Precipitable Water from 10 km Above Tropopause to the T = -40°C Level - Independent Data

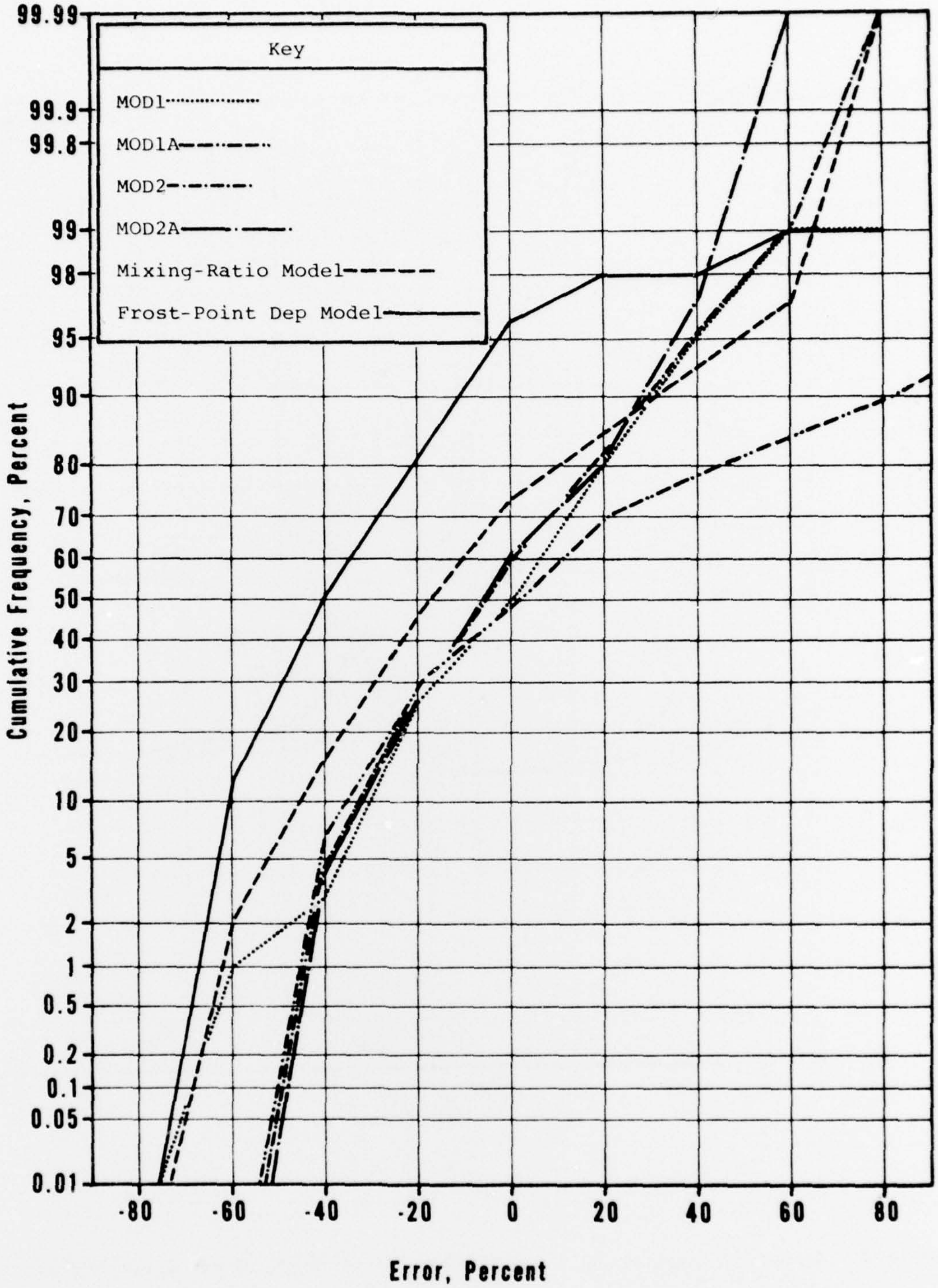

Figure 3. Cumulative Frequency of Error in Precipitable Water in Column from 10 km Above Tropopause to the T = -40°C Level - Dependent Data

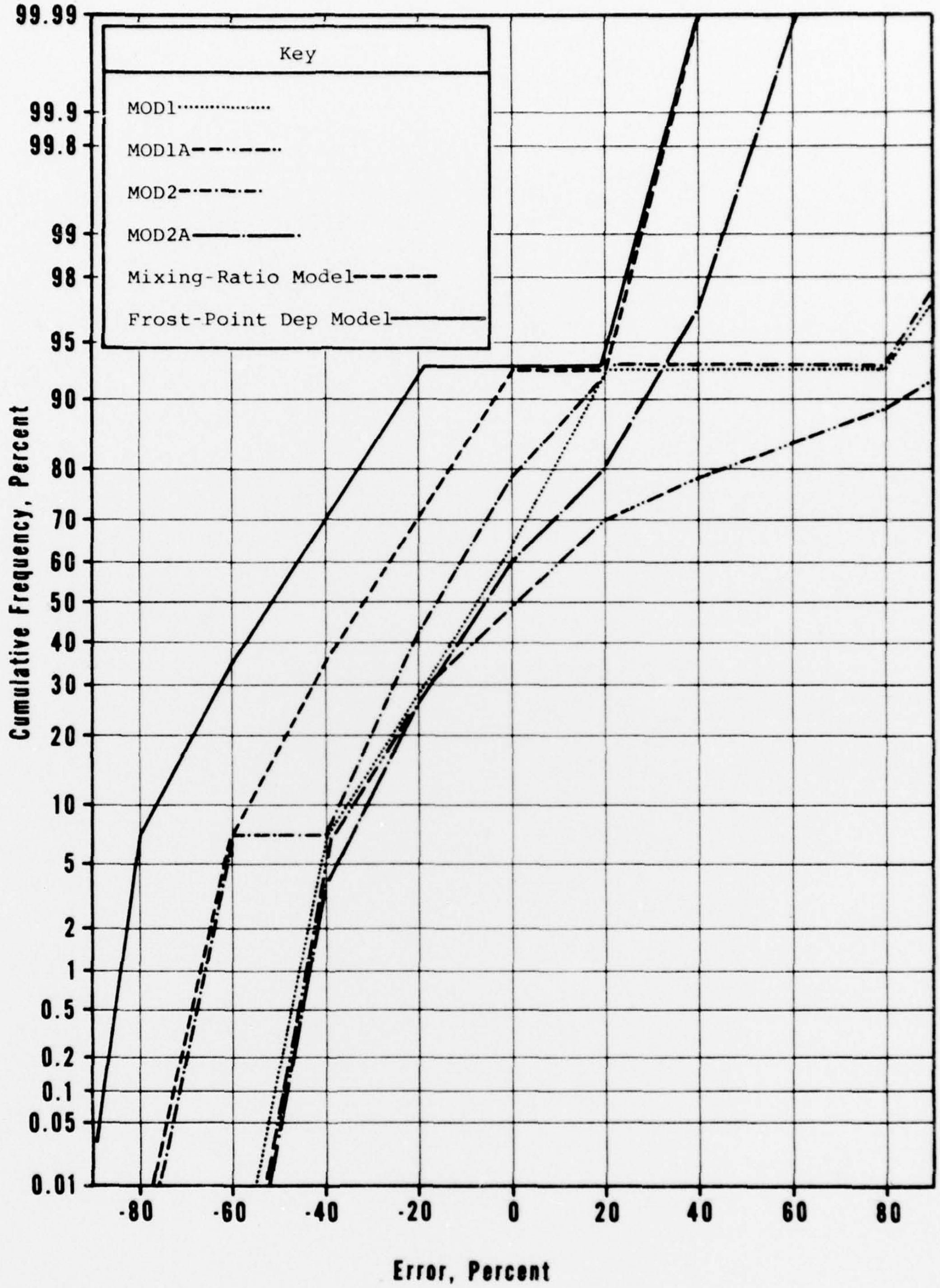

Figure 4. Cumulative Frequency of Error in Precipitable Water in Column from 10 km Above Tropopause to the T = -40°C Level - Independent Data